Deep-Water Ambient Noise Profiling; Marine Sediment Acoustics; and Doppler Geo-Acoustic Spectroscopy

Michael J. Buckingham
Marine Physical Laboratory
Scripps Institution of Oceanography
University of California, San Diego
9500 Gilman Drive, La Jolla, CA 92093-0238
phone: (858) 534-7977 fax: (858) 534-7641 email: mbuckingham@ucsd.edu

Grant Number: N00014-10-1-0092
http://extreme.ucsd.edu

LONG-TERM GOALS

1) Deep-water ambient noise profiling Profile the spectral, temporal and spatial properties of ambient noise from the surface to the bottom of the deepest ocean trenches over a broad frequency range (3 Hz – 40 kHz).

2) Marine sediment acoustics Develop a unified, physics-based model of sound wave and shear wave propagation in saturated, unconsolidated marine sediments.

3) Doppler geo-spectroscopy Develop the use of a light aircraft as a sound source in an inversion technique for returning the geo-acoustic parameters of the seabed in shallow water.

OBJECTIVES

1) The scientific objective of the deep-water ambient noise research is to measure the ambient noise in the deep ocean as a function of depth, from the sea surface to the seabed, in the deepest ocean trenches. This includes the Challenger Deep in the Mariana Trench, at a depth of almost 11 km. Of particular interest is the behavior of the noise at and below the critical depth. Environmental and system data will also be depth-profiled, including temperature, salinity, pressure and sound speed, along with all system motions (yaw, pitch, roll and horizontal/vertical translations). Theoretical modeling of the spectral, spatial and temporal properties of the ambient noise will also be performed.

2) The sediment acoustics research is aimed at developing a unified theory of wave propagation in marine sediments in the form of two sets of dispersion relations, one for compressional and the other for shear waves. Besides the frequency dependencies of the wave speeds and attenuations, these expressions will also return the dependence of the wave parameters on the geo-acoustic properties of the sediment, including porosity, density, grain size and overburden pressure.

Report Documentation Page

Form Approved OMB No. 0704-0188

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **Deep-Water Ambient Noise Profiling; Marine Sediment Acoustics; and Doppler**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of California, San Diego,Scripps Institution of Oceanography,9500 Gilman Drive,La Jolla,CA,92093-0238**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

3) The Doppler geo-acoustic spectroscopy technique is in support of the sediment acoustics research, providing a means of measuring the sound speed in the sediment at frequencies between 80 and 1000 Hz.

APPROACH

1) Deep-water ambient noise profiling A deep-diving Autonomous Instrument Platform (AIP) known as Deep Sound has been designed and developed by two members of my research group, Fernando Simonet (engineer) and David Barclay (graduate student). Deep Sound consists of a Vitrovex glass sphere housing a microprocessor, along with data acquisition and storage electronics. External to the sphere are several hydrophones (bandwidth 3 Hz – 40 kHz, and calibrated under high hydrostatic pressure to equivalent depths of 7 km), which may be arranged in various configurations, and an environmental sensor package (CTD). The system is untethered (autonomous), descending under gravity at a rate of 0.6 m/s, and, after dropping a weight at a pre-assigned depth, returning to the surface under buoyancy at the same rate. Throughout the descent and ascent, acoustic and environmental data are continuously recorded. Three beacons (high intensity strobe, radio antenna, and Argos GPS) aid recovery of the system. Numerous fail-safe devices are onboard, intended to ensure that the weight is indeed dropped, thus allowing the system to return to the surface.

   In support of the experimental work with Deep Sound, I am developing an analytical model of ambient noise in the deep ocean. The theoretical model is based on a bi-exponential sound speed profile, which resembles profiles found in the deep ocean inasmuch as it exhibits a sound speed minimum, and thus acts as a waveguide in which sound is trapped and may propagate for long distances. An advantage of the model is that it allows the temporal and spatial properties of the noise to be examined in the vicinity of the conjugate depth.

2) Marine sediment acoustics My theoretical approach involves the development of the compressional and shear wave dispersion relations, based on inter-granular interactions. In the latest version of the grain-shearing theory, the viscosity of the pore fluid is included in the analysis, which leads to low frequency (< 10 kHz) compressional wave behavior that is in accord with measurements made during the ONR-supported Sediment Acoustics Experiment 1999 (SAX 99). At higher frequencies, above 10 kHz, the effect of pore fluid viscosity is negligible and again the new theory fits the compressional wave data.

3) Doppler geo-acoustic spectroscopy A light aircraft flown at low level over the ocean acts as a sound source, which is used as the basis of an inversion technique for extracting the recovering the speed of sound in the seabed. The sound from the aircraft consists of a series of harmonics, typically 80, 160, 240, ….. Hz. Some of this acoustic energy penetrates the sea surface and reflects off the seabed, picking up information about the sediment in the process. From recordings made on hydrophones in the water column and/or buried in the seabed, an inversion is performed which returns the phase speed of the compressional wave in the sediment. Once the compressional speed is known, the remaining geo-acoustic parameters are estimated using the correlations provided by the grain-shearing theory.

WORK COMPLETED

Two versions of Deep Sound are now operational, designated the Mk. I and Mk. II. Both were deployed to a depth of 9 km on the Mariana Trench in November 2009, and both returned to the surface with high-quality ambient noise data sets for the whole water column. An invited paper[1] on the Deep Sound AIP has been published in a special issue of the *Journal of the Marine Technology Society* commemorating the Golden Anniversary of the dive of the manned submersible *Trieste* to the bottom of the Challenger Deep. The design of Deep Sound Mk. III is complete, and includes instrumentation additional to that on its predecessors, including a sing-around sound speed sensor, for comparison with computed sound speed from CTD measurements, and a high-resolution tri-axial accelerometer package, which will return all system motions, allowing the current-speed depth-profile to be determined.

A theoretical analysis of spatial coherence and cross-correlation in anisotropic ambient noise fields has been completed and a paper[2] submitted for publication in the *Journal of the Acoustical Society of America*.

The latest version[3] of the grain-shearing theory of wave propagation in marine sediments has been completed and published in the *Journal of the Acoustical Society of America*.

RESULTS

Deep Sound Mk. I and Mk. II were both deployed to a depth of 9 km in the Mariana Trench in November 2009, where they continuously recorded ambient noise data, along with environmental information, on the descent and the ascent. The spectral level of the noise was found to increase slightly with increasing depth, even through the critical depth, by an amount that depends on frequency. During an earlier deployment of Mk. I in the Philippine Sea in May 2009, the sound of several rain storms was captured by the system, and is clearly visible in the spectrograms.

The theoretical treatment of cross-correlation in spatially homogeneous, anisotropic ambient noise fields identifies the conditions necessary for extraction of the Green's function from the noise. Several examples of anisotropy are considered in the analysis, including Cron and Sherman's[4] deep-water ambient noise field. In that particular case, because of the surface reflection, the Green's function depends on the depth of the transducers, whereas the cross-correlation function is independent of absolute position in the water column. It is, therefore, impossible in this case to recover the Green's function from the noise.

The compressional and shear wave dispersion curves emerging from the grain shearing theory of wave propagation in marine sediments show good agreement with the SAX 99 measurements of sound speed and attenuation and shear speed and attenuation over a frequency range from 1 – 400 kHz. The compressional wave attenuation, in particular, is well represented by the theory, showing a linear dependence on frequency above 10 kHz, but transitioning into a frequency-squared dependence at lower frequencies, in excellent agreement with the data.

IMPACT/APPLICATIONS

Deep Sound has the potential for making ambient noise measurements to a depth of 11 km in the ocean. Our Mk. I and II systems have already recorded ambient noise data, along with environmental information, to a depth of 9 km in the Mariana Trench. These are the deepest measurements of ambient noise ever made. Deep Sound has a unique capability, which is important in connection with the resurgence of interest in deep-water ocean acoustics. If successful, Deep Sound Mk. III will be the fourth vehicle ever to return from the bottom of the deepest part of the ocean, the Challenger Deep in the Mariana Trench. The first descent was by the ONR-supported Trieste in 1960, with Don Walsh and Jacques Picard on board. It was some 35 years before the second descent, by the Japanese ROV Kaikõ in 1995, which was subsequently lost; and the third descent was by WHOI's hybrid ROV/AUV Nereus in May 2009.

TRANSITIONS

The acoustic and environmental data acquired by Deep Sound Mk. I during the Philippine Sea deployments have been provided to QinetiQ North America (Dr. Greg Duckworth). Their team is working under DARPA contract on the Deep Sea Operations Program (DSOP), and they needed Philippine Sea data in the 4-6 km depth range in order to support their development program on large acoustic arrays using standard optical fibers and a novel fiber interrogator. In particular, they needed information on the noise environment below the critical depth and temperature data below the critical depth, both of which we were able to provide.

The BBC is making a documentary film on deep-sea exploration systems to commemorate the descent of Trieste to the bottom of the Challenger Deep in January 1960. A segment on our Deep Sound AIP is to be included in the film.

RELATED PROJECTS

As previously reported.

REFERENCES

1. D. R. Barclay, F. Simonet and M. J. Buckingham, "Deep Sound: a free-falling sensor platform for depth-profiling ambient noise in the deep ocean ", *Mar. Tech. Soc. J.* **43**, 144-150 (2010)

2. M. J. Buckingham, "On the two-point cross-correlation function of anisotropic, spatially homogeneous ambient noise fields in the ocean and its relationship to the Green's function", *J. Acoust. Soc. Am.* (2010)

3. M. J. Buckingham, "Response to 'Comments on "Pore fluid viscosity and the wave properties of saturated granular materials including marine sediments [*J. Acoust. Soc. Am.* **122**, 1486-1501 (2007)]"'", *J. Acoust. Soc. Am.* **127**, 2099-2102 (2010)

4. B. F. Cron and C. H. Sherman, "Spatial correlation functions for various noise models", *J. Acoust. Soc. Am.* **34**, 1732-1736 (1962); and *J. Acoust. Soc. Am.* **38**, 885 (1965)

PUBLICATIONS

Journal Articles & Chapters in Book

1. M. J. Buckingham, "On the two-point cross-correlation function of anisotropic, spatially homogeneous ambient noise fields in the ocean and its relationship to the Green's function", *J. Acoust. Soc. Am.* (2010) [submitted, refereed]

2. M. J. Buckingham, "Response to 'Comments on "Pore fluid viscosity and the wave properties of saturated granular materials including marine sediments [*J. Acoust. Soc. Am.* **122**, 1486-1501 (2007)]"'", *J. Acoust. Soc. Am.* **127**, 2099-2102 (2010) [published, refereed]

3. D. R. Barclay, F. Simonet and M. J. Buckingham, "Deep Sound: a free-falling sensor platform for depth-profiling ambient noise in the deep ocean ", *Mar. Tech. Soc. J.* **43**, 144-150 (2010) [published, refereed]

4. D. R. Barclay and M. J. Buckingham, "On the shapes of natural sand grains", *J. Geophys. Res.* **114**, B02209, doi:10, 1-12 (2009) [published, refereed]

5. S. D. Lynch, G. D'Spain and M. J. Buckingham, "Temporal variability of narrow-band tones in a very shallow coastal waveguide", *J. Acoust. Soc. Am.*, (2008) [submitted, refereed]

6. M. J. Buckingham, "On the transient solutions of three acoustic wave equations: van Wijngaarden's equation, Stokes' equation and the time-dependent diffusion equation", *J. Acoust. Soc. Am.*, **124**, 1909-1920 (2008) [published, refereed]

7. M. J. Buckingham, "On pore-fluid viscosity and the wave properties of saturated granular materials including marine sediments", *J. Acoust. Soc. Am.*, **122**, 1486-1501 (2007) [published, refereed]

8. M. J. Buckingham and E. M. Giddens, "Theory of sound propagation from a moving source in a three-layer Pekeris waveguide", *J. Acoust. Soc. Am.*, **120**, 1825-1841 (2006) [published, refereed]

9. M. J. Buckingham and E. M. Giddens, "On the acoustic field in a Pekeris waveguide with attenuation in the bottom half-space", *J. Acoust. Soc. Am.*, **119**, 123-142 (2006) [published, refereed]

10. M. J. Buckingham, "Causality, Stokes' wave equation and acoustic pulse propagation in a viscous fluid", *Phys. Rev. E.*, **72**, 026610(9) (2005) [published, refereed].

11. M. J. Buckingham, "Compressional and shear wave properties of marine sediments: comparisons between theory and data", *J. Acoust. Soc. Am.*, **117**, 137-152 (2005) [published, refereed].

12. M. J. Buckingham, "Acoustic remote sensing of the sea bed using propeller noise from a light aircraft," in *Sounds in the Sea: Introduction to Acoustical Oceanography*, edited by H. Medwin, (Cambridge University Press, Cambridge, 2005) pp. 581-597 [published, refereed].

13. P. D. Thorne and M. J. Buckingham, “Measurements of the form function and total scattering cross section for suspensions of sands,” *J. Acoust. Soc. Am.*, **116**, 2976-2890 (2004) [published, refereed].

14. M. J. Buckingham, “A three-parameter dispersion relationship for Biot’s fast compressional wave in a marine sediment,” *J. Acoust. Soc. Am.*, **116**, 769-776 (2004) [published, refereed].

15. M. J. Buckingham, “On the sound field from a moving source in a viscous medium,” *J. Acoust. Soc. Am.*, **114**, 3112-3118 (2003) [published, refereed].

16. T. R. Hahn, T. K. Berger, and M. J. Buckingham, “Acoustic resonances in the bubble plume formed by a plunging water jet,” *Proc. Roy. Soc. Lond.* A, **459**, 1751-1782 (2003) [published, refereed].

17. M. J. Buckingham, E. M. Giddens, F. Simonet and T. R. Hahn, “Propeller noise from a light aircraft for low-frequency measurements of the speed of sound in a marine sediment,” *J. Comp. Acoust.*, **10** (4), 445-464 (2002) [published, refereed].

18. M. J. Buckingham, E. M. Giddens, J. B. Pompa, F. Simonet and T. R. Hahn, “Sound from a light aircraft for underwater acoustics experiments?,” *Acta Acust. united with Acust.*, **88** (5), 752-755 (2002) [published, refereed].

19. M. J. Buckingham and M. D. Richardson, “On tone-burst measurements of sound speed and attenuation in sandy marine sediments,” *IEEE J. Ocean. Eng.*, **27** (3), 429-453 (2002) [published, refereed].

20. M. J. Buckingham and M. S. Garcés, “Airborne acoustics of explosive volcanic eruptions,” *J. Comp. Acoust.*, **9** (3), 1215-1225 (2001) [keynote address, published, refereed].

21. N. G. Lehtinen, S. Adam, G. Gratta, T. K. Berger and M. J. Buckingham, “Sensitivity of an underwater acoustic array to ultra-high energy neutrinos,” *Astroparticle Phys.*, **697**, 1-14 (2001) [published, refereed].

22. M. D. Richardson, K. B. Briggs, D. L. Bibee, P. A. Jumars. W. B. Sawyer, D. B. Albert, T. K. Berger, M. J. Buckingham, *et al.*, “Overview of SAX99: environmental considerations,” *IEEE J. Ocean. Eng.*, **26** (1), 26-53 (2001) [published, refereed].

23. M. J. Buckingham, “Precision correlations between the geoacoustic parameters of an unconsolidated, sandy marine sediment,” *J. Comp. Acoust.*, **9** (1), 101-123 (2001) [published, refereed].

24. M. J. Buckingham, “Wave propagation, stress relaxation, and grain-to-grain shearing in saturated, unconsolidated marine sediments,” *J. Acoust. Soc. Am.*, **108**, 2796-2815 (2000) [published, refereed].

25. C. L. Epifanio, J. R. Potter, G. B. Deane, M. L. Readhead, and M. J. Buckingham, "Imaging in the ocean with ambient noise: the ORB experiments," *J. Acoust. Soc. Am.*, **106**, 3211-3225 (1999) [published, refereed].

26. M. J. Buckingham, "Theory of compressional and transverse wave propagation in consolidated porous media," *J. Acoust. Soc. Am.*, **106**, 575-581 (1999) [published, refereed].

27. M. J. Buckingham, "On the phase speed and attenuation of an interface wave in an unconsolidated marine sediment," *J. Acoust. Soc. Am.*, **106**, 1694-1703 (1999) [published, refereed].

28. M. J. Buckingham, "Acoustic daylight imaging in the ocean," in *Handbook on Computer Vision and Applications*, vol. 1, Sensors and Imaging, B. Jähne, H. Haubecker, and P. Geibler, Eds. San Diego: Academic Press, 1999, pp. 415-424 [published, refereed].

29. M. J. Buckingham, "Acoustic pulse propagation in dispersive media," in *New Perspectives on Problems in Classical and Quantum Physics. Part II. Acoustic Propagation and Scattering - Electromagnetic Scattering*, vol. 2, P. P. Delsanto and A. W. Sáenz, Eds. Amsterdam: Gordon and Breach, 1998, pp. 19-34 [published, refereed].

30. M. J. Buckingham, "Theory of compressional and shear waves in fluid-like marine sediments," *J. Acoust. Soc. Am.*, **103**, 288-299 (1998) [published, refereed].

31. G. B. Deane, M. J. Buckingham, and C. T. Tindle, "Vertical coherence of ambient noise in shallow water overlying a fluid seabed," *J. Acoust. Soc. Am.*, **102**, 3413-3424 (1997) [published, refereed].

32. N. M. Carbone, G. B. Deane, and M. J. Buckingham, "Estimating the compressional and shear wave speeds of a shallow-water seabed from the vertical coherence of ambient noise in the water column," *J. Acoust. Soc. Am.*, **103**, 801-813 (1997) [published, refereed].

33. M. J. Buckingham, "Sound speed and void fraction profiles in the sea surface bubble layer," *Appl. Acoust.*, **51**, 225-250 (1997) [published, refereed].

34. M. J. Buckingham and N. M. Carbone, "Source depth and the spatial coherence of ambient noise in the ocean," *J. Acoust. Soc. Am.*, **102**, 2637-2644 (1997) [published, refereed].

35. M. J. Buckingham, "Theory of acoustic attenuation, dispersion, and pulse propagation in unconsolidated granular materials including marine sediments," *J. Acoust. Soc. Am.*, **102**, 2579-2596 (1997) [published, refereed].